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L. Ootes and D.R. Lentz

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Occurrence of bleached mafic flows and their association with stockwork sulphides and banded iron-formation in the Crestaurum Formation of the late Archean Yellowknife Greenstone Belt, Northwest Territories[1,2]

L. Ootes and D.R. Lentz

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Abstract: In the northern part of the late Archean Yellowknife Greenstone Belt, tholeiitic basalt of the Crestaurum Formation is bleached along a 7 km strike length. Unbleached late volcanic gabbro dykes and sills transect the bleached mafic flows and constrain the alteration to synvolcanic processes. Bleaching is likely a result of silicification and Fe leaching with later chloritization of pillow selvages. These altered flows are intercalated with thinly layered, silica-rich, metavolcaniclastic rocks, which have been referred to as 'cherty tuff'. Petrographic and oxygen isotopic constraints indicate that the chert component is minor. An occurrence of discontinuous chert-magnetite iron-formation and discordant sulphide stockwork are indicative of synvolcanic hydrothermal activity. This hydrothermal activity is likely responsible for local alteration of the mafic flows, but does not explain the large-scale alteration. Stratigraphic considerations suggest that a hydrothermal alteration system existed within the Crestaurum Formation and preceded eruption of the overlying felsic metavolcanic rocks.

Résumé : Dans la partie septentrionale de la ceinture de roches vertes de Yellowknife de l'Archéen tardif, on trouve du basalte tholéiitique de la Formation de Crestaurum qui a été blanchi sur une distance de 7 km parallèlement à la direction. Des dykes et des filons-couches de gabbro tardivolcaniques non blanchis recoupent les coulées mafiques blanchies et permettent d'attribuer l'altération à des processus synvolcaniques. Le blanchiment résulte vraisemblablement de la silicification, du lessivage de Fe et de la chloritisation ultérieure des bordures de coussins. Ces coulées altérées sont intercalées de minces couches de roches métavolcanoclastiques riches en silice, que l'on a appelées «tuf cherteux». Les données sur la pétrographie et les isotopes de l'oxygène indiquent que le chert est une composante mineure. La présence de formation de fer à chert-magnétite discontinue et d'un stockwork de sulfures discordant témoigne d'activité hydrothermale synvolcanique. Bien que cette activité hydrothermale ait probablement altéré les coulées mafiques à l'échelle locale, elle n'explique toutefois pas l'altération à grande échelle. Des facteurs stratigraphiques laissent supposer qu'un réseau d'altération hydrothermale existait dans la Formation de Crestaurum avant l'éruption des roches métavolcaniques felsiques sus-jacentes.

[1] Contribution to EXTECH III
[2] Contribution to Targeted Geoscience Initiative

INTRODUCTION

The study area is located 15 km north of Yellowknife, Northwest Territories, and is underlain by metavolcanic rocks of the late Archean Yellowknife Greenstone Belt (Fig. 1). This sequence is host to the Crestaurum shear-zone-hosted gold deposit, the principal focus of this EXTECH III study. To define controls and timing constraints on gold deposition, it is necessary to understand the host-rock lithology. An extensive zone of bleached (whitish) metavolcanic rocks of the Crestaurum Formation occurs southeast of the Crestaurum mine area (Fig. 1, 2, 3). It extends laterally along strike for approximately 7 km from the West Bay Fault to the east, to the Yellowknife River Fault Zone to the west, and across the stratigraphy to the southeast. Regional mapping by Henderson and Brown (1966) correctly identified these rocks (in the opinion of the authors) as having a basaltic to andesitic basalt protolith.

The Yellowknife Greenstone Belt is best known for shear-zone-hosted gold deposits in metavolcanic and metaturbiditic rocks that collectively have produced over 400 t of gold (Poulsen et al., 2000). Significant volcanogenic massive sulphide deposits do occur in the Slave Province, but because they are located in remote areas, they have not been exploited (Padgham, 1992). It has been suggested that the Yellowknife Greenstone Belt is not an ideal candidate for volcanogenic massive sulphide exploration (Goodwin, 1988) as the felsic metavolcanic rocks have light rare-earth-element-enriched patterns and insignificant Eu anomalies (Goodwin, 1988; Cousens, 2000) compared to the relatively flat rare-earth-element patterns and large Eu anomalies of felsic metavolcanic rocks associated with volcanogenic massive sulphide deposits in the Superior Province (e.g. Lesher et al., 1985). Small volcanogenic massive sulphide-like deposits have been identified near Homer Lake in the northern part of the Yellowknife Greenstone Belt (Padgham, 1992), but are uneconomic. The minor occurrence of banded iron-formation and stockwork sulphides in proximity to mixed felsic and mafic metavolcaniclastic and bleached mafic metavolcanic rocks in the Crestaurum area is evidence of extensive seafloor hydrothermal activity possibly related to volcanogenic massive sulphide genesis. Therefore, the host rocks of the Crestaurum shear-zone-hosted gold deposit may have been enriched in base metals during seafloor alteration prior to gold deposit formation.

ANALYTICAL TECHNIQUES

Samples for whole-rock geochemical analysis and $\delta^{18}O$ were collected during the 2000 field season. All weathered surfaces were cut off and samples were washed and individually wrapped in resealable bags. Geochemical analysis and $\delta^{18}O$ were completed at Activation Laboratories Ltd., Ancaster, Ontario. Samples were crushed, mechanically split, and pulverized using a mild steel mill to minus 150 mesh. Major elements, Zr, V, and Y were analyzed by fusion inductively coupled plasma emission spectrometry (ICP-ES). Trace elements and rare-earth elements were analyzed by digestion inductively coupled plasma mass spectrometry (ICP-MS). Analyses for Au, As, Cr, Sb, and Sc were done by instrumental neutron activation analysis (INAA). In-house rock standard (GB-1; Lentz, 1995) was submitted to selectively assess the data quality. Major elements are quoted with less than 4% error, except for K_2O, which has a 14% error. Trace elements tend to have a higher degree of variance, particularly those of low abundance, but most trace elements have errors less than 25%. Part of the variance may be attributed to the analytical techniques used. Whole-rock $\delta^{18}O$ values have a precision of 0.2‰.

GEOLOGY OF THE YELLOWKNIFE GREENSTONE BELT

The late Archean Yellowknife Greenstone Belt is a 12 km thick, northeast-trending, southeast-dipping and younging, homoclinal belt of tholeiitic to calc-alkaline metavolcanic rocks in the southwestern Archean Slave Structural Province (Henderson and Brown, 1966; Helmstaedt and Padgham, 1986; Cousens, 2000). It is considered to be a parautochthonous cover sequence that disconformably overlies the >2830 Ma Central Slave Cover Group and the >2900 Ma Central Slave Basement Complex (Isachsen and Bowring, 1997; Bleeker et al., 1999). It is overlain by ca. 2660 Ma Duncan Group metagreywacke-mudstone turbidite (Bleeker, 1996) and unconformably by ca. 2605 Ma Jackson Lake Formation polymictic conglomerate and sandstone (Fig. 1; Isachsen, 1992). Helmstaedt and Padgham (1986) subdivided it into the ca. 2722 to 2701 Ma Kam Group and the 2680 to 2660 Ma Banting Group (Isachsen, 1992).

Structural and metamorphic evolution

The Yellowknife Greenstone Belt has undergone at least three stages of Archean deformation, the nomenclature for which has been extrapolated from the Duncan Lake Group turbidite units (Fig. 1) that overlie the greenstone belt to the east (Bleeker and Beaumont-Smith, 1995). First-generation deformation (D_1) predates granitoid intrusion and is defined by pillow flattening and local foliations (S_1) with local isoclinal folds (F_1) in the volcaniclastic rocks. The second stage of deformation (D_2) is defined by penetrative fabrics (S_2) that are axial planar to belt-scale, asymmetrical Z-folds. Although S_2 fabrics are found in the mafic volcanic rocks, they are best observed in the felsic volcaniclastic units. Third-generation fabrics (S_3) are well developed in the Jackson Lake Formation and occur as a result of sinistral shear on the Yellowknife Greenstone Belt. The Yellowknife Greenstone Belt was not in the shortening field (i.e. not folded), although local S_3 crenulation cleavages were developed in S_2 (W. Bleeker, pers. comm., 2002). All rock types in the Yellowknife Greenstone Belt have been offset by Proterozoic faults (e.g. West Bay Fault; Fig. 1).

Intrusion of Defeat Suite plutonic rocks (2630–2620 Ma; Davis and Bleeker, 1999) into the Yellowknife Greenstone Belt (Fig. 1) created metamorphic aureoles that parallel the intrusive contacts. These aureoles grade outward from

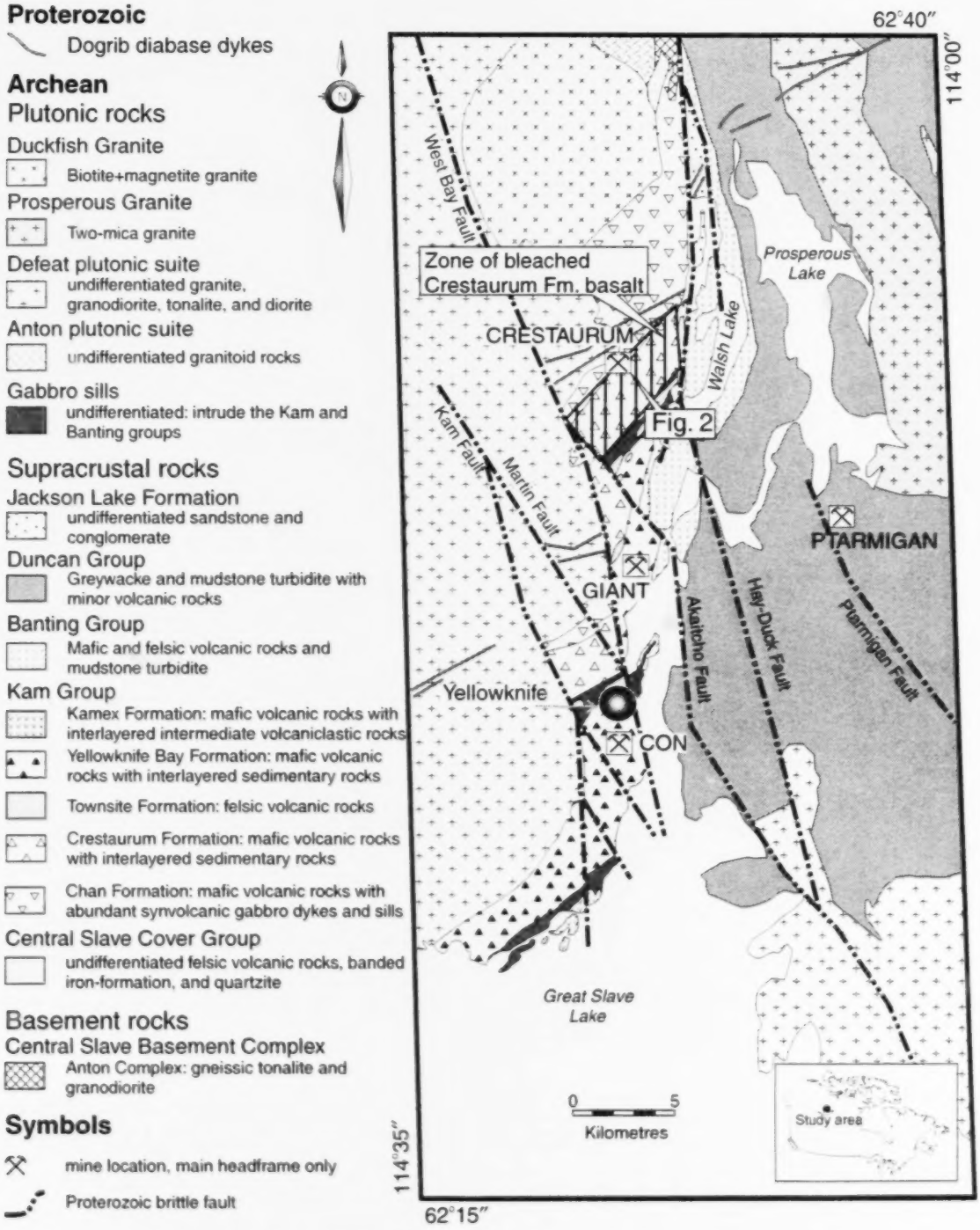


Figure 1. *Geology of the Yellowknife Greenstone Belt and the southern portion of the Yellowknife Domain. Information: zone of bleached Crestaurum Formation mafic flows (vertical hatching)* (modified from *Helmstaedt and Padgham, 1986*)*: Central Slave Basement Complex and Central Slave Cover Group (Bleeker et al., 1999), and Kamex Formation (Cousens and Falck, 2000).*

amphibolite through transitional (or epidote amphibolite) to greenschist grade (Boyle, 1961; McDonald et al., 1993; Thompson, 2001). This metamorphic event is suggested to overprint a regional greenschist-grade metamorphic event that began before and continued after intrusion of the Defeat Suite plutonic rocks (Thompson, 2001). All rock types considered herein have been metamorphosed so the prefix 'meta' has been dropped from this point forward.

Geology of the Kam Group

This study focuses on rock types of the lower Kam Group. Helmstaedt and Padgham (1986) changed the Kam Formation to group status and subdivided it into four formations; from base to top these are the Chan, Crestaurum, Townsite, and Yellowknife Bay formations; a fifth, the Kamex Formation, was added by Cousens and Falck (2000).

The Chan Formation comprises basaltic flows that have been extensively intruded by synvolcanic and postvolcanic gabbro dykes (MacLachlan and Helmstaedt, 1995) and lacks

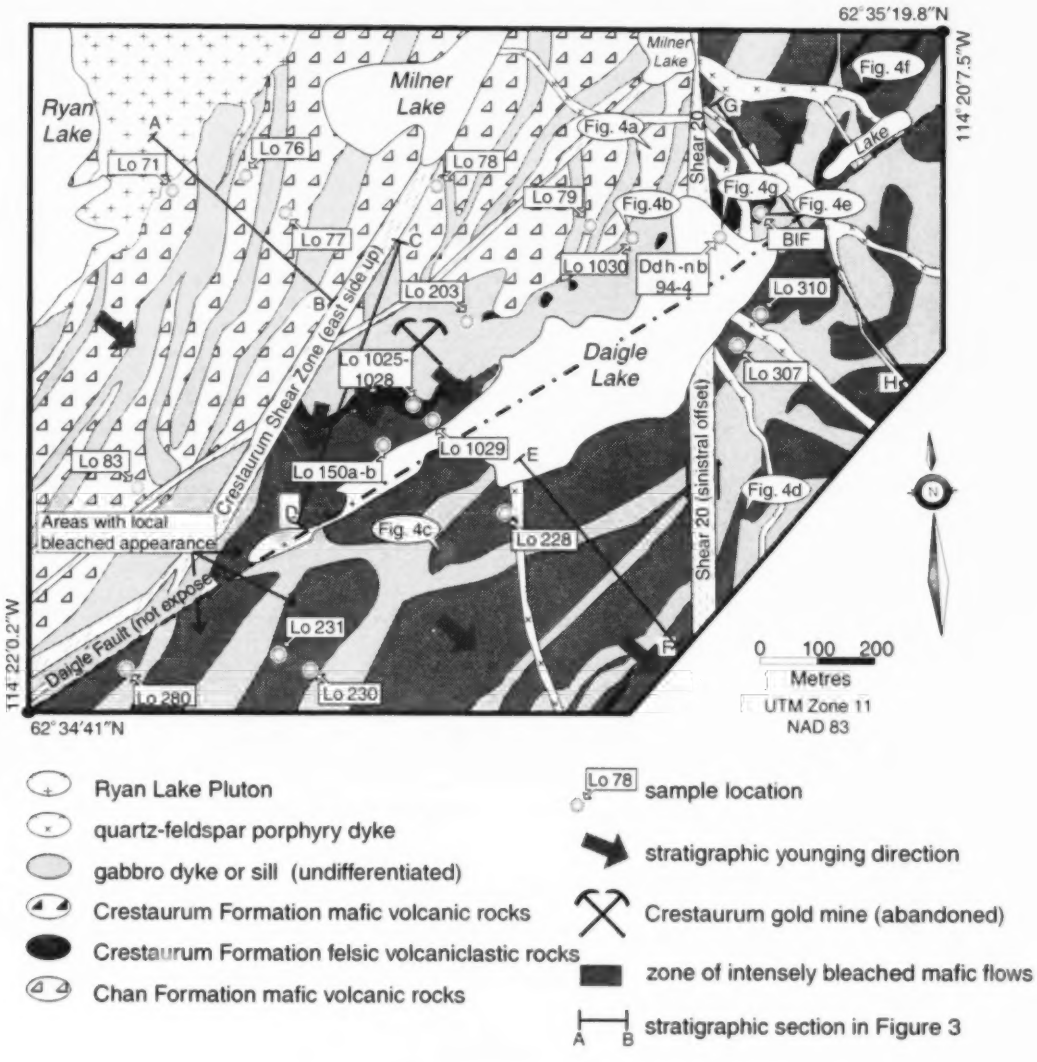


Figure 2. *Simplified geology of the Crestaurum mine area. Areas of intense altertation, sample locations, and figure locations presented in the paper are shown. Stratigraphic younging directions are defined by pillow textures and flow-top breccia in the mafic volcanic rocks and by graded bedding and flame structures in the volcaniclastic rocks* (modified from *Ootes, 2002*).

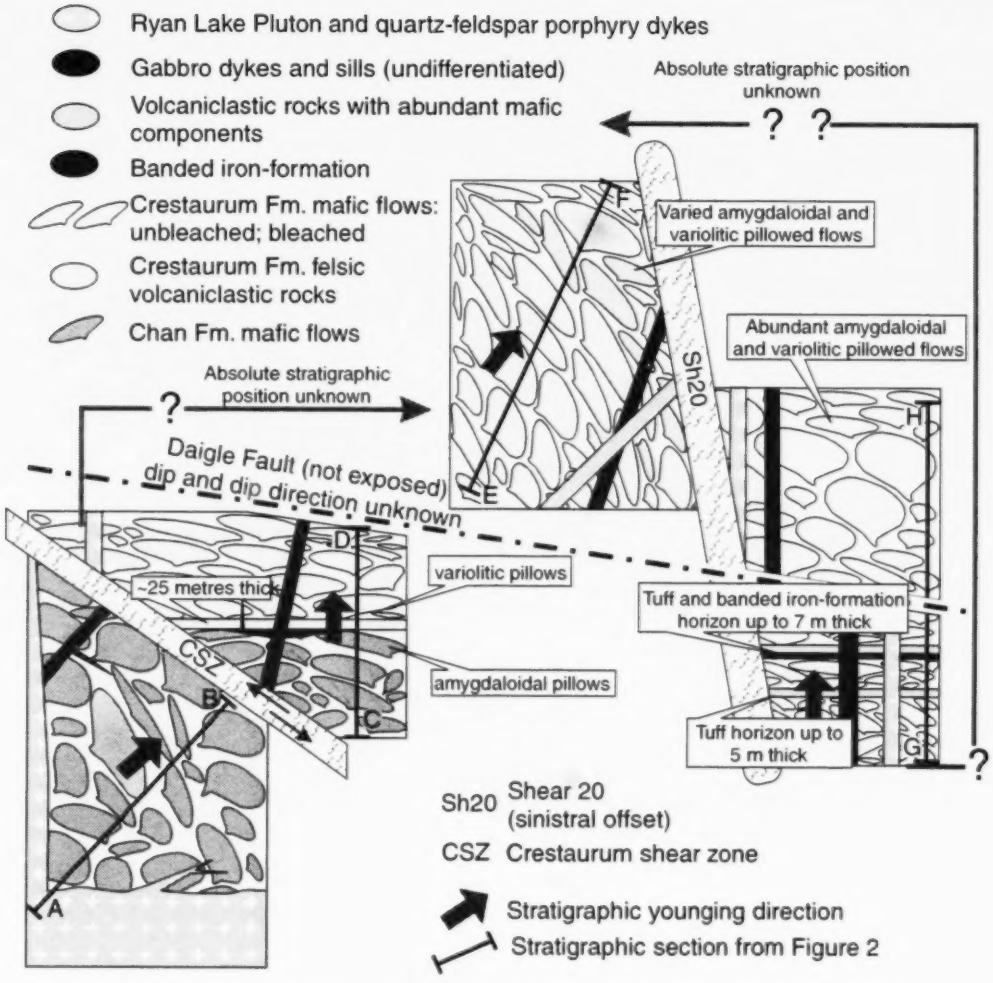


Figure 3. *Idealized stratigraphic section (not to scale) of the Chan and Crestaurum formations in the Crestaurum mine area. Offset along Shear 20 has transposed bleached mafic flows, banded iron-formation, and related volcaniclastic units to an apparent lower stratigraphic position. Sections compiled from mapping by Henderson and Brown (1966) and Ootes (2002).*

felsic volcaniclastic members (Helmstaedt and Padgham, 1986). The Crestaurum Formation is dominated by basaltic flows that locally have a pervasive bleached appearance. A number of felsic volcaniclastic horizons 1 to 20 m thick occur within the Crestaurum Formation, which also has fewer synvolcanic and postvolcanic gabbro dykes than the Chan Formation (Helmstaedt and Padgham, 1986).

Immediately overlying the Crestaurum Formation are the rhyolitic and dacitic rocks of the Townsite Formation that have been dismembered by large postvolcanic gabbro dykes (Henderson and Brown, 1966; Helmstaedt and Padgham, 1986). Yellowknife Bay Formation basaltic andesite and volcaniclastic rocks overlie the Townsite Formation (Helmstaedt and Padgham, 1986). Basaltic andesite and intermediate volcaniclastic rocks of the Kamex Formation occur at the top of the Kam Group (Cousens and Falck, 2000; Fig. 1).

Seafloor-altered mafic flows have been identified in the Yellowknife Bay Formation in the southern part of the Yellowknife Greenstone Belt (e.g. McDonald et al., 1993). Only minor portions of the Crestaurum Formation and even less Chan Formation are exposed in the southern part of the belt. These Crestaurum and Chan formation rocks include some seafloor-altered mafic flows (e.g. local garnet porphyroblasts within altered pillowed flows), but for the most part do not have the extensive bleached appearance of the Crestaurum Formation pillowed flows in the area of the Crestaurum mine.

GEOLOGY OF THE CHAN AND CRESTAURUM FORMATIONS IN THE CRESTAURUM MINE AREA

The Crestaurum mine area (Fig. 2), located 15 km north of Yellowknife, is underlain by Chan Formation mafic volcanic flows and Crestaurum Formation bleached mafic volcanic flows and volcaniclastic rocks. The stratigraphic exposure and laterally traceable bleached mafic flows (Fig. 1) make this area a superb location to study the cause and effects of seafloor alteration in the Crestaurum Formation (Fig. 1, 2, 3). Previous studies in the area include mapping by Henderson and Brown (1966), a field-trip guide by Padgham (1987), a geochemical transect by Cunningham and Lambert (1989), U-Pb geochronology by Isachsen (1992), and a geochemical and Nd isotope transect by Cousens (2000).

Important structures in the area include the Crestaurum shear zone, Shear 20, and the Daigle Fault (Fig. 2). The Crestaurum shear zone trends 035°/55°SE and obliquely transects volcanic rocks and postvolcanic gabbro and quartz-feldspar porphyry dykes of the Chan and Crestaurum formations (Fig. 2). It hosts the Crestaurum gold deposit and field evidence (Ootes, 2002) indicates it is syn- to post-D_2 (≤2600 Ma; Davis and Bleeker 1999). Shear 20 is a well exposed shear zone that trends north, dips 85° to 90° east, and transects and displaces rocks of the Chan and Crestaurum formations. It has left laterally offset and juxtaposed younger Crestaurum Formation rocks against older Crestaurum and Chan formation rocks (Fig. 2; Ootes, 2002). This indicates that the felsic volcaniclastic rocks west of Shear 20 and the volcaniclastic rocks east of Shear 20 are not related (Fig. 2, 3, 4). The Daigle Fault is not exposed, but is defined by a 060° linear trend through the Crestaurum mine area (Fig. 2, 3) and is suggested to have minimal offset (Henderson and Brown, 1966).

Chan Formation

Rocks of the Chan Formation in the Crestaurum mine area are composed of dark to light green-weathered, amphibolite- to greenschist-grade (Thompson, 2001), pillowed to massive flow basalt and basaltic andesite. Numerous primary volcanic textures are evident in the basalt, including pillow selvages from 1 to 30 cm thick that locally indicate younging to the southeast, quartz and carbonate amygdales in upper stratigraphic flows, and polygonal cooling cracks in massive flow basalt. Primary minerals in these mafic volcanic flows include rare clinopyroxene (P. Thompson, pers. comm., 2001) and pseudomorphs of fine-grained muscovite after plagioclase phenocrysts. Near the top of the Chan Formation local areas of bleaching become evident (Fig. 4) and indicate that the process that bleached the Crestaurum Formation mafic flows had a minor effect on the upper Chan Formation mafic flows. Sample LO79 (Fig. 2, 4) has a moderately bleached appearance, but is geochemically similar to other Chan Formation pillowed flows (Table 1).

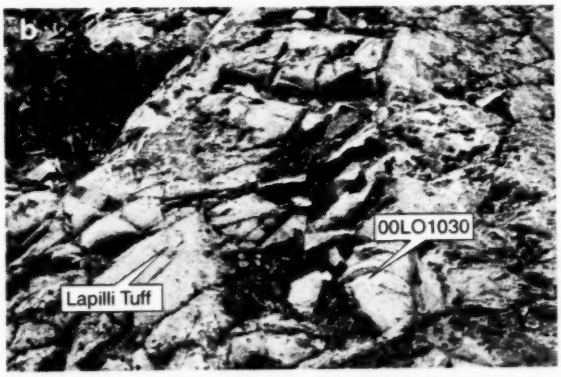
Chan Formation basalt is extensively intruded by at least three generations of late- to postvolcanic gabbro dykes and sills (Henderson and Brown, 1966; Ootes, 2002), which include 1) dark brown- to green-weathered, medium- to coarse-grained gabbro with radiating, locally irregularly shaped amphibole phenocrysts up to 1 cm (#7 dykes of Henderson and Brown, 1966), 2) dark brown- to black-weathered, fine- to medium-grained gabbro with plagioclase phenocrysts up to 2 cm (#8a dykes of Henderson and Brown, 1966), and 3) brown- to green-weathered, fine- to medium-grained gabbro (#8 dykes of Henderson and Brown, 1966).

Chan Formation basalt and postvolcanic gabbro dykes and sills are intruded by a multiphase granitic to quartz dioritic pluton 500 m west of the Crestaurum mine site (Fig. 2). This pluton is the likely source of numerous quartz-feldspar porphyry dykes (2658 ± 2 Ma, Isachsen, 1992; 2678 ± 8 Ma, Padgham, 1985) that trend southeast and cut all Kam Group rock types (Henderson, 1985; Ootes, 2002). This constrains the age of the gabbro dykes to older than about 2670 Ma. Some gabbro dykes were likely synchronous with mafic volcanism throughout the Kam Group (>2700 Ma).

Crestaurum Formation

The Crestaurum Formation is composed of a wider variety of rock types than the underlying Chan Formation. For simplicity, these rock types are described herein as they occur in stratigraphy. An intermixed unit of reworked felsic volcaniclastic rocks occurs at the base of the Crestaurum Formation. It is about 25 m thick with delicately laminated to 30 cm thick beds. Relic depositional structures include local graded bedding, flame structures, and syndepositional folding. Volcaniclastic beds have a plagioclase and quartz groundmass with subangular quartz phenoclasts (Fig. 4). Fine-grained tuffaceous beds are common with a groundmass of microcrystalline quartz and minor to abundant fine-grained muscovite and carbonate. Mafic volcanic clasts or relic volcanic fragments are common, but are now chlorite and epidote. Postdepositional structures include well preserved S_1 and S_2

Figure 4. ***a****) Moderately bleached pillowed flows with thick, chloritized pillow selvages near the top of the Chan Formation;* ***b****) Felsic volcaniclastic rocks at the base of the Crestaurum Formation;* ***c****) unbleached pillowed flow lower in the Crestaurum Formation;* ***d****) typical bleached pillowed flow with chloritic pillow selvages higher in the Crestaurum Formation;* ***e****) banded iron-formation;* ***f****) felsic and mafic volcaniclastic rocks that lie 50 m along strike and stratigraphically above the banded iron-formation;* ***g****) coarse-grained stockwork with pyrite, pyrrhotite, and magnetite in a chloritic groundmass;* ***h****) unbleached postvolcanic gabbro dykes transecting bleached pillow flows of the Crestaurum Formation. This figure is not shown on Figure 2, but represents a site about 2 km southwest of the location of Figure 2 along strike of the bleached pillow flows.*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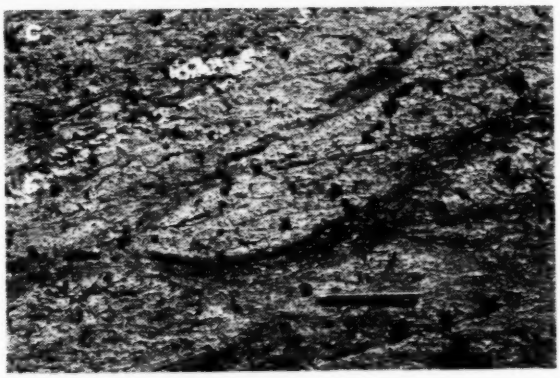
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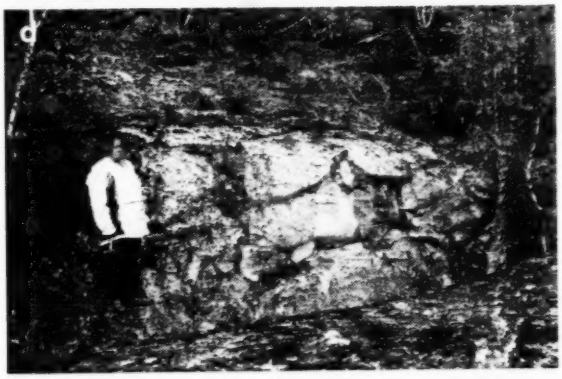
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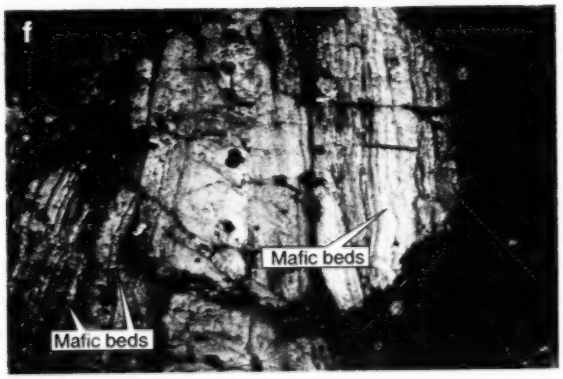
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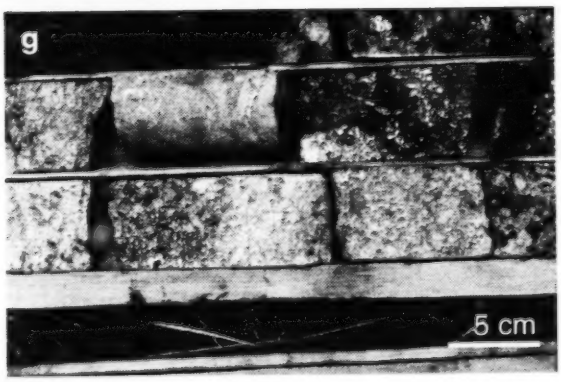
Mafic beds
Mafic beds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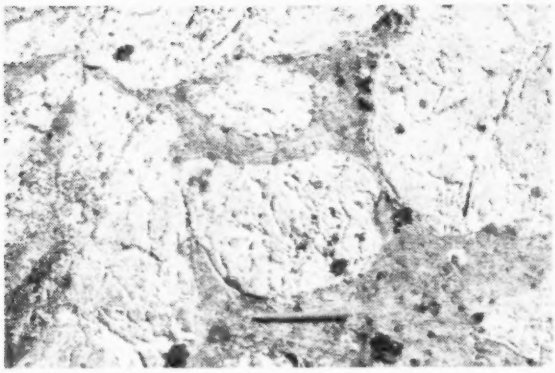
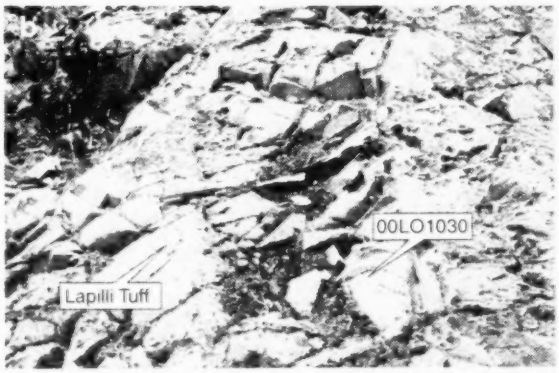
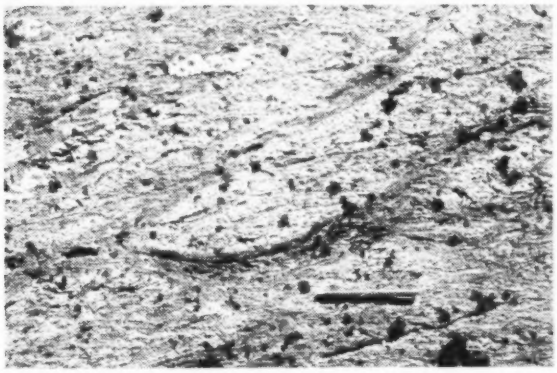
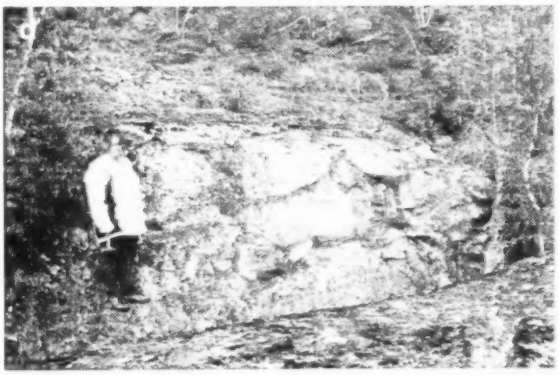
h
Contact
Gabbro
Bleached pillows




b
00LO1030
Lapilli Tuff

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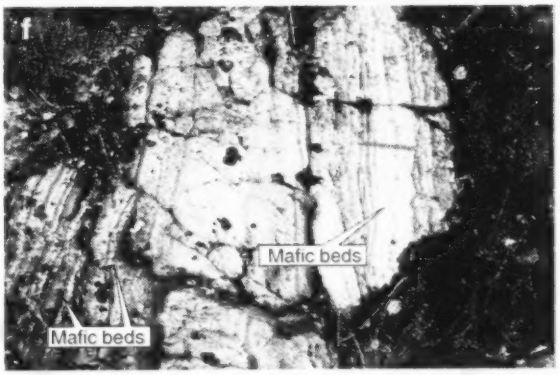
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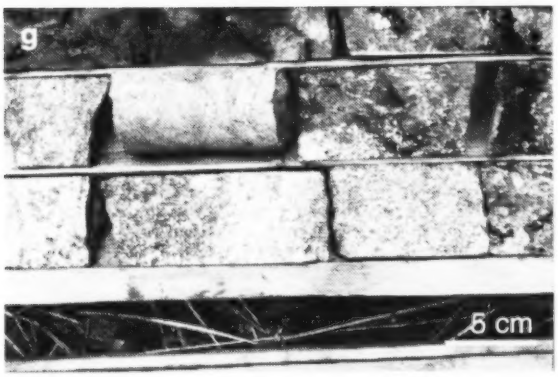
Mafic beds
Mafic beds


g
5 cm

Contact
Bleached pillows

Table 1. Whole-rock geochemical data for mafic volcanic rocks of the Chan and Crestaurum formations. Sample locations are shown on Figure 2.

	Chan Formation						Crestaurum Formation					Crestaurum Fm.- variolitic pillows			
Sample no. wt.%	00L071	00L076	00L077	00L078	00L079 bleached	00L083 porph. flow	00L0230 bleached	00L0231 bleached	00L0280 bleached	00L0307 bleached	00L0310 bleached	00L0150 'A'	00L0150 'B'	00L0228 altered	00L01029 altered
SiO_2	45.2	52.7	51.6	47.2	51.3	51.2	61.6	56.2	54.9	51.7	50.5	50.4	51.6	47.8	59.1
Al_2O_3	13.18	15.64	15.26	14.72	15.25	12.67	13.78	19.50	16.60	13.39	13.53	11.44	10.61	13.37	11.67
Fe_2O_3	14.86	11.71	9.79	16.16	11.57	18.11	6.16	8.91	8.04	8.70	8.65	13.92	14.66	9.60	7.89
MnO	0.30	0.21	0.24	0.35	0.21	0.32	0.14	0.11	0.19	0.20	0.19	0.29	0.30	0.26	0.19
MgO	8.94	4.59	5.20	7.23	4.40	3.33	2.75	3.65	5.24	7.23	7.08	9.30	9.07	5.50	4.29
CaO	11.79	10.18	11.83	7.93	12.85	9.92	5.44	4.35	9.32	9.97	11.26	9.70	10.49	11.93	6.05
Na_2O	1.24	2.24	1.01	2.33	0.74	1.65	3.36	1.59	2.33	2.16	1.51	0.80	0.69	1.10	3.53
K_2O	0.78	0.41	0.93	0.23	0.14	0.47	0.65	0.90	0.76	0.04	0.02	0.18	0.31	0.11	0.10
TiO_2	0.90	1.18	1.17	0.86	0.86	2.01	0.73	1.01	0.87	0.50	0.50	0.56	0.56	0.49	0.55
P_2O_5	0.07	0.14	0.10	0.07	0.08	0.20	0.06	0.11	0.09	0.06	0.06	0.05	0.05	0.05	0.06
LOI	2.40	1.42	1.45	2.39	2.75	0.19	4.87	3.01	1.28	5.72	6.86	2.41	1.93	9.06	5.66
TOTAL	99.7	100.4	98.6	99.4	100.1	100	99.5	99.4	99.6	99.7	100.1	99.1	100.3	99.3	99.1
ppm															
V	228	270	252	279	270	405	191	291	257	206	207	223	216	78	158
Co	63	48	34	65	52	38	62	60	64	45	43	63	59	43	69
Ni	79	74	89	133	122	20	157	245	197	192	71	111	190	180	167
Cr	180	266	270	268	269	42	409	569	521	437	438	727	735	396	849
Sc	40	34	34	42	41	44	31	50	46	46	46	46	45	44	31
Cu	230	46	27	205	87	73	116	99	33	54	89	<10	87	94	51
Zn	159	106	51	147	98	75	69	80	74	87	69	96	99	77	33
Ga	17	19	15	18	17	22	14	20	19	15	15	12	12	11	9
Ge	1.0	1.3	0.8	1.1	1.4	1.3	0.9	1.6	0.9	1.0	0.9	1.5	2.0	0.6	0.7
Rb	27	22	40	2	6	10	16	18	30	<1	<1	5	11	1	4
Sr	110	150	127	63	166	78	78	64	149	111	94	99	89	93	110
Y	19	24	24	21	19	38	14	20	16	13	14	13	12	15	8
Zr	56	96	95	63	57	140	50	65	53	44	40	44	36	167	35
Hf	1.8	2.8	2.7	1.8	1.7	4.3	1.5	2.0	1.8	1.1	1.2	1.2	1.2	1.3	0.7
Nb	0.2	0.4	0.2	0.2	0.2	1.4	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Ta	0.15	0.36	0.35	0.14	0.14	0.37	0.12	0.18	0.17	0.10	0.09	0.10	0.10	0.08	0.07
Th	1.7	4.4	3.9	1.2	1.4	1.8	1.6	1.7	1.4	1.6	1.7	1.4	1.0	1.2	0.6
U	0.3	0.9	0.8	0.2	0.2	0.4	0.3	0.3	0.4	0.3	0.3	0.2	0.2	0.3	0.1
Cs	3.9	2.4	2.1	0.2	0.4	1.4	0.9	1.3	3.6	0.1	0.1	0.7	2.0	0.2	0.3
Ba	120	109	275	33	41	62	79	134	136	18	17	35	56	12	14
La	4.8	12.9	12.6	3.7	3.6	7.8	3.4	4.5	4.6	3.4	3.5	3.1	2.7	3.5	1.6
Ce	9.7	26.5	26.2	9.2	9.0	20.2	7.9	10.7	8.9	7.5	7.8	7.3	6.3	6.9	3.9
Pr	1.25	2.94	2.96	1.24	1.24	2.82	1.00	1.40	1.22	0.90	0.93	0.93	0.84	0.95	0.54
Nd	6.7	13.9	13.8	6.8	6.8	14.9	5.2	7.3	5.6	4.7	4.8	5.1	4.6	4.4	2.8
Sm	2.1	3.5	3.4	2.3	2.3	5.0	1.6	2.2	1.6	1.4	1.5	1.5	1.3	1.3	0.9
Eu	0.86	1.25	1.17	1.00	0.89	1.81	0.60	0.81	0.62	0.53	0.57	0.61	0.64	0.47	0.37
Gd	2.5	3.7	3.7	2.7	2.7	5.7	1.7	2.4	1.9	1.6	1.7	1.8	1.6	1.7	1.0
Tb	0.53	0.70	0.70	0.59	0.56	1.12	0.35	0.54	0.40	0.33	0.37	0.36	0.35	0.36	0.19
Dy	3.5	4.5	4.5	3.8	3.6	7.6	2.4	3.6	2.4	2.2	2.4	2.4	2.3	2.3	1.2
Ho	0.74	0.93	0.96	0.81	0.77	1.61	0.51	0.75	0.56	0.48	0.54	0.52	0.49	0.50	0.25
Er	2.3	2.9	3.0	2.7	2.5	5.0	1.5	2.4	1.6	1.5	1.7	1.5	1.6	1.6	0.8
Tm	0.34	0.43	0.45	0.40	0.38	0.77	0.23	0.34	0.24	0.22	0.26	0.24	0.23	0.22	0.11
Yb	2.35	2.77	2.89	2.55	2.44	5.18	1.47	2.09	1.51	1.50	1.70	1.55	1.58	1.42	0.71
Lu	0.36	0.42	0.44	0.40	0.37	0.82	0.22	0.30	0.23	0.23	0.28	0.25	0.24	0.24	0.11
W	29	1	1	<0.5	2	2	<0.5	1	1	<0.5	<0.5	1	<0.5	<0.5	>0.5
Tl	0.1	0.1	0.1	<0.05	0.1	0.1	0.1	0.1	0.2	<0.05	<0.05	<0.05	0.1	<0.05	<0.05
Pb	39	32	5	22	14	6	8	<5	8	10	6	14	8	<5	<5
Bi	3.5	2.7	1.1	0.9	11.5	4.2	0.3	0.3	1.0	0.1	0.2	1.4	5.6	0.1	0.7
As	17	33	11	3	31	3	13	10	5	2	1	3	4	1	21
Sb	17	25	30	8	22	10	5	5	10	4	4	8	8	3	6
Au (ppb)	<2	26	77	<2	<2	<2	9	15	12	<2	<2	332	3	14	7
Zr/TiO_2	0.006	0.008	0.008	0.007	0.007	0.007	0.007	0.006	0.006	0.009	0.008	0.008	0.006	0.034	0.006
La_n/Yb_n	1.46	3.33	3.12	1.04	1.05	1.08	1.64	1.54	2.18	1.63	1.47	1.42	1.23	1.77	1.59
Eu/Eu*	1.14	1.05	1.00	1.24	1.10	1.04	1.12	1.08	1.07	1.09	1.07	1.13	1.33	0.96	1.25
$\delta^{18}O_{(SMOW)}$	6.1	7.6	6.8	7.3	8.3	7.1	10.5	9.7	8.4	8.8	8.3	7.8		8.8	9.9

fabrics and F_1 and F_2 folds. Isachsen and Bowring (1997) termed these felsic volcaniclastic rocks the 'Crestaurum Chert' (chert has been dropped herein as no true chert has been identified) and defined a maximum age of 2827 Ma using U-Pb zircon geochronology. This is significantly older than the overall age of 2722 Ma suggested for this unit (Isachsen and Bowring, 1997) and is attributed to inheritance from the underlying Central Slave Cover Group (Isachsen and Bowring, 1997; Bleeker et al., 1999).

Immediately overlying the felsic volcaniclastic rocks are dark green-weathered variolitic pillowed flows of the Crestaurum Formation with preserved pillow selvages and varioles up to 0.5 cm. Ti. pillows are terminated and not correlative across the Daigle Fault (Fig. 2, 3). On the southeast side of the Daigle Fault and on the west side of Shear 20 (Fig. 2), the Crestaurum Formation consists of massive flows, variolitic pillowed flows, pillowed flows with quartz and minor carbonate amygdales, and pillowed flows with neither varioles nor amygdales. In most cases the pillowed flows have well preserved pillow selvages and where there is evidence of tops, they consistently young to the southeast. Some massive flows occur lower in the section; they are distinguished from the fine- to medium-grained gabbro by local bleached patches and rare flow breccia. The pillowed flows become increasingly bleached to the southeast (up the stratigraphy; Fig. 3, 4). Figures 4c and d show the difference between unbleached pillowed flows (Fig. 4c) lower in the stratigraphy and extensively bleached flows (Fig. 4d) higher up. Primary minerals have not been identified in the bleached pillowed flows and the groundmass has abundant fine-grained quartz, phyllosilicates, chlorite, and pyrite. Locally, the bleached pillowed flows contain a green-weathered phyllosilicate mineral that looks like fuchsite, but does not contain chromium or vanadium (H. Falck, pers. comm., 2000, regarding unpub. data of F. Santaguida). Local interflow sedimentary rocks are felsic volcaniclastic dominated with intermixed siltstone and sandstone.

The pillowed and massive flows of the Crestaurum Formation east of Shear 20 and north of the Daigle Fault are pervasively bleached below and above the volcaniclastic horizon. The bleached pillowed flows continue on the southeast side of the Daigle Fault, but the relationship to units on the north side is undefined (Fig. 2, 3). This extensively bleached zone of pillowed flows extends southeastward to the top of the Crestaurum Formation (Fig. 1). The volcaniclastic horizon east of Shear 20 consists of two units from 1 m to 7 m thick with finely laminated to 30 cm thick beds. The beds of the first unit are commonly fine to very fine grained, contain varied amounts of mudstone, siltstone, and mafic tuffaceous and felsic tuffaceous material, and are devoid of magnetite. Banded iron-formation characterizes the second unit and occurs within the volcaniclastic rocks (Fig. 3, 4), but is only traceable for 3 m. Its discontinuity can be explained by the intrusion of numerous gabbro and quartz-feldspar porphyry dykes that have inhibited correlation of the volcaniclastic units (Fig. 2). Fine-grained magnetite and Fe-rich chlorite compose the groundmass of the banded iron-formation.

Abundant base-metal-bearing pyrite, pyrrhotite, and magnetite in quartz and carbonate veins were identified in drillhole DDH-NB-94-4, completed by Nebex in 1994 (Fig. 2). They are interpreted as a stockwork sulphide feeder zone formed by low-temperature hydrothermal venting on the seafloor. These stockworks have been identified only in this drillhole and do not outcrop. They contain coarse-grained pyrite with grains up to 2 cm, medium-grained pyrrhotite, and fine- to medium-grained, disseminated magnetite within quartz and calcite stringers and veins; they are hosted within highly altered mafic volcanic rocks (Fig. 4g).

The gabbro dykes and sills that cut the Chan Formation also transect the Crestaurum Formation. They are unbleached and stand out not only relative to the Crestaurum Formation bleached flows at outcrop scale (Fig. 4h), but also on a 1:20 000 colour airphoto. As previously mentioned, they must be older than about 2670 Ma and the oldest dykes are likely synchronous with mafic volcanism in upper formations of the Kam Group (>2700 Ma; Isachsen and Bowring, 1997). This constrains the alteration of the Crestaurum Formation mafic flows to older than 2700 Ma, suggesting a synvolcanic origin.

GEOCHEMICAL AND OXYGEN ISOTOPE CONSIDERATIONS

Lithogeochemical and oxygen isotope ($\delta^{18}O_{SMOW}$) data for a variety of Chan and Crestaurum formation pillowed flows are presented in Table 1. The geochemical analyses of the Chan Formation mafic flows are consistent with their unbleached physical appearance. Their $\delta^{18}O$ values, which fall within the range of typical subaqueous basaltic flows (Muehlenbachs, 1998), attest to their unbleached nature. Sample LO83 has different physical and chemical attributes compared to other mafic flows. It has a fine-grained groundmass with plagioclase phenocrysts up to 1 cm, similar to a #8a dyke (Henderson and Brown, 1966), but is transected by a #7 gabbro dyke and has been interpreted as a porphyritic massive flow (Henderson and Brown, 1966; Ootes, 2002). Crestaurum Formation pillowed flows have higher SiO_2 values and lower $Fe_2O_3{}^T$ values than Chan Formation pillowed flows, consistent with their bleached appearance. This, and a corresponding increase of $\delta^{18}O_{(SMOW)}$ with SiO_2 content, is evidence that the bleaching resulted from Fe leaching and/or silica dumping during pervasive hydrothermal alteration.

Variolitic pillowed flows of the Crestaurum Formation are also included in Table 1. Three of the samples have geochemical and $\delta^{18}O_{SMOW}$ values that are consistent with the bleached and moderately bleached samples of the Chan and Crestaurum formations. Sample 1029 was collected about 1 m above the felsic volcaniclastic horizon (Fig. 2) and is moderately sheared and altered. This accounts for the variation of the chemical constituents of this sample compared to other variolitic pillowed flows.

Lithogeochemistry and $\delta^{18}O_{SMOW}$ of the felsic volcaniclastic rocks west of Shear 20 and the banded iron-formation and stockwork sulphides (Fig. 2) are presented in Table 2.

Table 2. Whole-rock geochemical data for Crestaurum Formation felsic volcaniclastic rocks, banded iron-formation, and stockworks from drillhole DDH-NB-94-4. Sample locations are shown on Figure 2.

	Felsic volcaniclastic rocks and banded iron-formation							Drillhole DDH-NB-94-4			
Sample no. wt.%	**LO1025**	**LO1026**	**LO1027**	**LO1028**	**LO1030**	**LO203**	**BIF**	**NB-94-4** 902′	**NB-94-4** 925′	**NB-94-4** 945′	***NB-94-4** 830′–832′
SiO_2	69.6	81.3	75.7	71.5	78.5	73.8	56.4	5.7	45.4	18.1	
Al_2O_3	14.34	9.58	13.43	14.98	11.07	14.09	8.34	0.42	12.23	3.93	1.98
Fe_2O_3	2.77	1.43	1.71	2.06	1.62	1.85	24.06	52.12	15.96	37.67	54.06
MnO	0.06	0.03	0.02	0.04	0.05	0.03	0.63	0.26	0.52	1.00	0.30
MgO	1.79	0.80	0.82	1.17	0.68	0.54	5.50	1.86	5.65	2.61	2.13
CaO	3.97	1.87	1.66	2.63	1.88	1.05	0.99	9.31	9.84	18.76	3.92
Na_2O	0.88	0.31	0.56	0.71	4.13	3.98	0.01	(0.01)	(0.01)	0.04	0.03
K_2O	2.97	2.75	3.60	3.76	0.87	2.29	0.06	(0.01)	0.02	0.06	0.02
TiO_2	0.21	0.14	0.18	0.21	0.17	0.21	0.24	0.02	1.87	0.15	0.08
P_2O_5	0.06	0.06	0.06	0.06	0.07	0.07	0.07	(0.01)	0.23	0.02	0.02
LOI	3.83	2.14	2.37	3.03	1.25	1.12	4.18	20.71	7.12	8.85	
TOTAL	100.5	100.4	100.1	100.2	100.3	99.0	100.5	90.4	98.8	91.2	
ppm											
V	26	6	13	14	9	21	62	13	281	44	47
Co	1	1	5	2	4	3	10	54	53	9	101
Ni	<20	53	699	<20	<20	<20	47	31	32	44	<40
Cr	28	13	23	30	58	70	13	10	162	21	26
Sc	3	2	3	3	2	3	23	5	32	8	12
Cu	<10	<10	21	16	16	<10	28	47	<10	25	113
Zn	36	<30	<30	<30	<30	<30	78	805	125	309	142
Ga	19	8	11	14	8	17	13	1	21	8	
Ge	<0.5	<0.5	0.6	<0.5	0.6	0.6	0.5	<0.5	0.8	<0.5	
Rb	60	36	61	70	18	81	<1	5	<1	<1	45
Sr	74	27	43	54	49	84	4	61	260	64	29
Y	4	2	3	3	3	4	35	4	31	18	10
Zr	73	70	78	73	67	89	167	12	97	55	
Hf	2.3	1.5	1.8	1.5	1.5	2.5	5.1	<0.1	2.9	0.6	1.0
Nb	0.2	0.2	0.2	0.2	0.2	0.2	5.4	<0.2	2.7	<0.2	
Ta	0.11	0.07	0.10	0.07	0.10	0.18	0.72	0.02	0.37	0.16	<0.5
Th	2.0	1.1	1.5	1.3	1.4	2.3	14.3	5.4	1.3	4.0	2.3
U	0.4	0.3	0.3	0.3	0.4	0.6	3.5	0.7	0.2	1.0	<0.5
Cs	3.2	1.4	2.5	3.5	0.6	4.3	<0.1	<0.1	0.2	0.2	<0.1
Ba	116	90	124	143	98	344	<3	<3	<3	<3	<50
La	7.3	3.4	4.1	4.7	3.4	6.1	51.4	1.3	8.3	8.9	6.7
Ce	15.0	7.4	8.3	9.7	7.3	12.1	81.8	2.1	23.5	15.8	12.0
Pr	1.56	0.84	0.92	1.07	0.88	1.25	8.03	0.27	3.31	1.87	
Nd	6.3	3.3	3.5	4.1	3.7	5.1	34.3	1.2	17.3	7.6	9.0
Sm	1.1	0.6	0.6	0.7	0.7	0.8	6.8	0.3	5.0	1.7	1.0
Eu	0.40	0.19	0.20	0.24	0.25	0.31	1.19	0.07	1.76	0.39	<0.2
Gd	0.9	0.5	0.5	0.6	0.6	0.8	6.3	0.5	5.0	2.2	
Tb	0.12	0.07	0.08	0.08	0.09	0.12	0.99	0.09	0.95	0.36	<0.5
Dy	0.6	0.4	0.4	0.5	0.5	0.7	6.2	0.6	5.5	2.2	
Ho	0.12	0.08	0.08	0.09	0.10	0.14	1.31	0.14	1.10	0.47	
Er	0.3	0.2	0.2	0.3	0.3	0.5	4.3	0.5	3.3	1.4	
Tm	0.05	0.03	0.04	0.03	0.04	0.07	0.66	0.08	0.45	0.20	
Yb	0.31	0.22	0.21	0.22	0.26	0.47	4.27	0.50	2.93	1.35	1.00
Lu	0.04	0.03	0.03	0.03	0.04	0.07	0.70	0.07	0.41	0.23	0.18
Tl	0.2	0.1	0.1	0.2	<0.05	0.3	<0.05	<0.05	<0.05	<0.05	
Pb	5	<5	6	<5	<5	6	10	206	11	<5	10
Bi	0.4	<0.1	0 ^	0.2	0.1	0.8	1.7	<0.1	1.0	<0.1	11.0
As	1	1		3	3	6	1	64	5	5	93
Sb	5	3	3	3	3	7	5	7	4	2	11
Au (ppb)	7	<2	2	<2	<2	<2	<2	85	<2	<2	51
Zr/TiO_2	0.035	0.051	0.044	0.035	0.040	0.042	0.070	0.049	0.005	0.036	
La_n/Yb_n	16.80	11.19	14.25	15.52	9.65	9.36	8.64				
Eu/Eu	1.27	1.04	1.09	1.16	1.17	1.17	0.55				
$\delta^{18}O^*_{(smow)}$	10.5	11.1		10.4	10.5	10.1					

NOTE: Sample *NB-94-4 (830′–832′) analyzed by INAA only.

The felsic volcaniclastic samples have similar major, trace, and rare-earth elements and Zr/TiO_2 ratios, consistent with a volcaniclastic origin. The narrow range of $\delta^{18}O_{SMOW}$ values, with the highest value coincident with the highest SiO_2 values, further supports a predominant volcaniclastic rather than a chemical origin (Knauth and Epstein, 1976). However, some chemically precipitated rocks (i.e. chert) are likely to occur in the package. The banded iron-formation is composed of 24.1 weight per cent $Fe_2O_3^T$ with no anomalous precious or base-metal values. Four samples of stockwork sulphides, collected at 252 m, 273 m, 280 m, and 286 m respectively, indicate locally anomalous contents of Zn (805 ppm), Pb (206 ppm), Cu (113 ppm), and Au (85 ppb).

DISCUSSION

The spatial association between banded iron-formation and the stockwork sulphides (Fig. 2) suggests that exhalative components are proximally related to the development of the synvolcanic stockwork feeder zone. Liaghat and MacLean (1992) used mass balance calculations and a tuff-exhalative mixing model to show the igneous and exhalative proportions in the Key Tuffite at Matagami, Quebec. In our study, a precursor tuffaceous component was not identified so mass balance calculations were not undertaken. The banded iron-formation unit was likely a product of exhalative activity during which Fe and Si were chemically precipitated after seafloor hydrothermal venting.

The bleached mafic flows could be related to hydrothermal activity linked to the development of the stockwork feeder systems in the sequence. As the stockwork system developed and hydrothermal fluids circulated through the volcanic pile, Fe may have been leached from the pillows leaving abundant silica and alkali elements (Table 1), leading to the bleached appearance. The bleaching may also be a result of silica dumping, possibly coupled with the dissolution of Fe. The selvages of the bleached pillows are chloritized (Fig. 4) and may be explained by the development of a large hydrothermal circulation system in the volcanic package, evident by the extensive area of bleached flows (Fig. 1). As the volcanic pile thickened, the previously bleached pillowed flows were buried deeper into a zone where chloritization dominated (e.g. Franklin, 1996). Fluids working through the volcanic pile at this depth would likely follow the easiest flow path, in this case the pillow selvages. This generated bleached or 'silicified' mafic volcanic rocks with chloritized selvages. The best way to quantify the extent of alteration is to perform mass-balance calculations to define 'real' gains and losses of elements. Mass-balance calculations were not performed here as most samples were derived from different flows, some with distinct geochemical signatures. As well, a 'least altered' sample from the Crestaurum Formation was not found as unbleached and pillowed flows generally contained abundant carbonate and quartz stringers throughout.

Relating the bleached pillowed flows to the stockwork sulphides can only be done on a local scale. The hydrothermal event that formed the banded iron-formation and stockwork may account for localized bleaching; however, bleached flows occur stratigraphically above this horizon, indicating that the main bleaching event was most likely linked to an episode of volcanism that postdated banded iron-formation deposition, but preceded the eruption of the overlying Townsite Formation. The aerial extent and similarity of these bleached mafic flows to altered flows associated with volcanogenic massive sulphide deposits, in particular those of Noranda (Gibson et al., 1983) and Matagami (MacGeehan, 1977), highlight the possibility of undiscovered volcanogenic massive sulphide deposits in the Yellowknife Greenstone Belt.

CONCLUSIONS

Crestaurum Formation metavolcanic rocks in the Yellowknife Greenstone Belt are bleached for about 7 km along strike and almost entirely across strike. Unbleached gabbro dykes and sills transect the bleached volcanic rocks of the Crestaurum Formation and the unbleached volcanic rocks of the Chan Formation. Some gabbro sills and dykes are likely synchronous with mafic volcanism within the Kam Group, suggesting they are older than about 2700 Ma. This constrains the alteration in the Crestaurum volcanic rocks to older than 2700 Ma, during building of the volcanic pile on the seafloor. The occurrence of banded iron-formation, stockwork sulphides, and silicified Crestaurum mafic flows in close proximity is strong evidence of hydrothermal activity and venting on the seafloor. This is only a local phenomenon, however, and the pervasive silicification of Crestaurum Formation mafic flows can only be explained by a large-scale hydrothermal event beneath and probably near the base of the overlying Townsite Formation. Although it has been suggested the Yellowknife Greenstone Belt is an unlikely candidate for volcanogenic massive sulphide deposits, the similarity between the bleached mafic flows and those of Noranda and Matagami, Quebec, leaves open the possibility of a yet undiscovered volcanogenic massive sulphide deposits in the Yellowknife Greenstone Belt.

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